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REEXAMINING BEST MANAGEMENT PRACTICES FOR IMPROVING WATER QUALITY IN URBAN WATERSHEDS[1]

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ABSTRACT: Municipalities will be implementing structural best management practices at increasing rates in their effort to comply with Phase II of the National Pollutant Discharge Elimination System (NPDES). However, there is evidence that structural best management practices (BMPs) by themselves may be insufficient to attain desired water quality standards. This paper reports on an analysis of the median removal efficiencies of structural BMPs and compares them to removal efficiencies estimated as being necessary to attain water quality standards in the Rouge River in Detroit, Michigan. Eight water quality parameters are reviewed using data collected from 1994 to 1999 in the Rouge River. Currently, five of the eight parameters in the Rouge River including bacteria, biochemical oxygen demand, and total suspended solids (TSS) exceed the required water quality standards. The reported analysis of structural BMP efficiencies reveals that structural BMPs appear capable of reducing only some of the pollutants of concern to acceptable levels.

(KEY TERMS: nonpoint source pollution; storm water management; urban water management; water treatment; water quality; watershed management.)

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INTRODUCTION

Municipalities have been responsible for ensuring local water quality in their rivers and streams for years (Berry *et al.,* 1996). Section 401 of the Clean Water Act of 1972 (CWA) prohibits the discharge of pollutants from a point source into waters of the United States (U.S.) unless the discharge has been authorized by a National Pollutant Discharge Elimination System (NPDES) permit. Congress mandated a storm water permitting program in the 1987 amendments to the CWA. Under Phase I of the program, communities began specifically addressing storm water management. Phase I of the CWA uses NPDES permits to address storm water runoff from: (1) medium and large municipal separate storm sewer systems (MS4s) serving populations of 100,000 or more; (2) construction activities that disturb five acres of land or more; and (3) ten categories of industrial activities. More recently, the U.S. Environmental Protection Agency (USEPA) issued final regulations for the next phase of the CWA. USEPA's NPDES Revisions Addressing Storm Water Discharges (USEPA, 1999) (commonly referred to as Phase II) specifically addresses nonpoint source pollution and is the next step in fulfilling the CWA's mandate of restoring and maintaining the chemical, physical, and biological integrity of the nation's waters. Phase II requires operators of MS4s in urban areas with populations less than 100,000 and operators of construction sites of less than five acres to obtain NPDES permits and implement practices to control polluted storm water runoff. U.S. municipalities must meet Phase II requirements for managing storm water before March 2003 (USEPA, 1999).

There are six elements to storm water management under Phase II: public education and outreach, public participation, illicit discharge detection and elimination, construction site runoff control, post-construction runoff control, and pollution prevention/good housekeeping. However, the most common response for many communities attempting to

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eliminate and prevent storm water pollution has been the implementation of structural BMPs (Roesner *et al.,* 2001; Urbonas, 2001). Structural BMPs for storm water (sometimes called structural storm water treatment practices) are physical undertakings and construction projects used to reduce the levels of pollutants in storm water runoff to improve water quality. Six typical storm water structural BMPs are: dry and wet ponds, wetlands, filtering and infiltration practices, and swales (ASCE, 2000; CWP, 2000). This paper evaluates the efficacy and potential benefit of these six structural BMPs for improving water quality in an urban watershed.

SOME PREVIOUS RESEARCH

In response to Phase I storm water pollution requirements, an increased number of structural BMPs were implemented by communities in their attempt to control pollution from urban runoff (Barrett, 2000; Roesner *et al.,* 2001). The objective of a number of studies has been to assess the ability of storm water treatment practices such as wet ponds, grass swales, wetlands, sand filters, and dry detention basins to reduce pollutant discharges associated with storm water runoff (CWP, 1997, 2000; ASCE, 2000; Urbonas, 2001). However, inconsistent study methods, lack of detailed design information, and the failure to adequately report protocols have made wide scale assessment of structural management practices difficult (Jones, 2001; Strecker *et al.,* 2001). Recently, the second edition of the National Pollutant Removal Performance Database (CWP, 2000), prepared by the Center for Watershed Protection (CWP), raised doubts about the ability of structural BMP to protect waters downstream from urban discharges (Roesner *et al.,* 2001). In line with such findings, Tom Schueler, executive director of CWP, shared his belief that structural BMP do not adequately protect downstream aquatic environments from urban runoff (Roesner *et al.,* 2001).

RESEARCH QUESTIONS

The reported research tests the hypothesis that structural BMPs do not adequately reduce the concentrations and/or mass of pollutants of concern in the runoff to the Rouge River to levels necessary to meet current surface water quality standards. Furthermore, the research tests the hypothesis that as the percentage of impervious area in a watershed increases (i.e., an area becomes more urbanized), the ability of structural BMPs to remove the required concentrations and mass of pollutants of concern decreases.

RESEARCH METHOD

The reported research is based on an analysis of water quality data from the Rouge River National Wet Weather Demonstration Project (RRNWWDP, 2000). The reported analysis uses the Rouge River water quality data to estimate the percentage of removal of pollutants necessary based on current standards for eight pollutants of concern (POC). This analysis compares the necessary removal rates to the generally accepted removal efficiencies of six common structural BMPs. Doing so allows for an examination of whether the structural BMP seem likely to meet the water quality standards for the Rouge River. Furthermore, the analysis stratifies the results by the research area's prevailing percentage of impervious land cover in order to examine any variability associated with different levels of urbanization.

The RRNWWDP undertook an extensive effort to accurately determine levels of impervious area and the percentage of directly connected area (DCIA) for each of 10 land use categories within the Rouge River's 11 subwatersheds (RRNWWDP, unpublished, 1994, Camp Dresser McKee Memorandum: Determination of Impervious Area and Directly Connected Impervious Area). The most recent digital land use data (1990) were obtained by RRNWWDP and used to create 10 land use geographic information system (GIS) layers that were consistent with land use categories in other national studies of pollutant loads. The percentages of impervious area and DCIA for each of the land use categories, together with knowledge of the total acres of each land use type within each subwatershed, were used to calculate area weighted values of percent impervious area and percent DCIA for each subwatershed (RRNWWDP, unpublished, 1994, Camp Dresser McKee Memorandum: Determination of Impervious Area and Directly Connected Impervious Area). The GIS model and data were ground truthed and verified by examining a total of about 300 sample areas using aerial photographs and field observations (RRNWWDP, unpublished, 1994, Camp Dresser McKee Memorandum: Determination of Impervious Area and Directly Connected Impervious Area). As a result, the reported analysis is undertaken at the watershed and subwatershed levels, while BMPs themselves generally operate at much smaller scales.

The method used in this analysis of comparing median POC values with general BMP removal rates, while useful, should be approached with caution.

Limitations in such an approach relate primarily to spatial, temporal, and other variables. Variability within the watershed is an issue because spatial, temporal, or loading data do not exist to help frame BMP performance against the range of local conditions. Therefore, we present the first and fourth quartile for each POC in the study area as one way to capture and describe POC variability. Also, it must be pointed out that the results of the reported analysis are directly comparable to the original RRNWWDP watershed model, which does account for spatial and loading scenarios. The reported results are in general agreement with the RRNWWDP model result. Therefore, it seems reasonable to use the median pollutant levels for the eight POC and the median removal efficiencies for the six BMPs in the reported study. Additional limitations associated with the RRNWWDP data and monitoring results as well as the removal efficiencies of BMPs are discussed later in this paper.

Rouge River National Wet Weather Demonstration Project (RRNWWDP)

The Rouge River National Wet Weather Demonstration Project is a USEPA grant funded comprehensive program to manage wet weather pollution and restore water quality in the Rouge River, a tributary of the Detroit River in southeastern Michigan (RRNWWDP, 2001a). The Rouge River is more than 126 miles in length with four separate branches covering an area of approximately 466 square miles (Figure 1). The Rouge River watershed encompasses all or part of 48 municipalities in three counties and is connected to more than 400 lakes, impoundments, and ponds. With a population of more than 1.5 million, the Rouge River watershed is the state's most urbanized land area, with only 25 percent of the land in the watershed remaining undeveloped (RRNWWDP, 2001a).

The state of Michigan has designated all surface waters to be protected for the following uses: (1) agriculture, (2) industrial water supply, (3) public water supply at the point of intake, (4) navigation, (5) warm water fisheries, (6) other indigenous aquatic life and wildlife, (7) partial body contact recreation, (8) total body contact recreation, and (9) cold water fisheries (Brown *et al.,* 2000). Those uses that apply to all reaches of the Rouge River include Items 5 through 8 and Item 9 in Johnson Creek. However, severe pollution problems in the Rouge River have limited the uses of the river throughout the watershed (RRNWWDP, 2001b).

The early focus of the RRNWWDP aimed at controlling combined sewer overflows (CSOs) in older urban core portions of downstream areas. The regulatory approach of issuing National Pollutant Discharge Elimination System (NPDES) permits mandating corrective action worked relatively well (Murray *et al.,* 1999). However, additional monitoring of the river after the Phase I permits were issued showed that storm water pollution needed to be controlled before full restoration of the river could be achieved. In response, a total of 60 pilot storm water management projects were implemented throughout the Rouge River watershed (Murray *et al.,* 1999). The structural storm water treatment practices implemented in the Rouge River area include: wetland creation and restoration, grassed swales and detention ponds, erosion controls, stream bank stabilization, and habitat restoration (RRNWWDP, 1996). The reported analysis focuses on the efficacies of six structural BMP (dry ponds, wet ponds, wetlands, filtering practices, infiltration practices, and swales) used along the Rouge River.

Rouge River Data

As mentioned above, the reported analysis uses publicly available data from the EPA sponsored Rouge River National Wet Weather Demonstration Project. The RRNWWDP reports following generally accepted data collection and water quality monitoring procedures (RRNWWDP, 1998). Monitoring of Rouge River water quality began in the fall of 1993 and continues on an annual basis. Field based data collection programs have been conducted along the Rouge on a seasonal basis, typically when air temperatures remain above freezing and the water temperature remains above 12°C (RRNWWDP, 1998).

The long term average annual precipitation for the Rouge watershed is 32.62 inches. Fifty-seven percent, or roughly 18.8 inches, of precipitation falls in the wet season, from April through September. The remaining 13.8 inches (43 percent) falls from October through March. Between 1994 and 1999, the year with the most rainfall was 1998, with 34.13 inches, while 1996 had the least rainfall, with 27.39 inches. The largest single event occurred on July 8, 1998, and was 4.34 inches. Runoff from this event was not sampled. Mean annual water temperature was 48.6°F and ranged from a low of 48.3°F in 1996 to a high of 53.5°F in 1998.

This paper focuses on eight pollutants of concern in the Rouge River: bacteria, biochemical oxygen demand, total Kjeldahl nitrogen (TKN), nitrate and nitrite nitrogen, total phosphorous, total suspended solids (TSS), total copper, and total zinc. These POC consistently constitute eight of the nine principal POC in urban runoff (Roesner *et al.,* 2001). Lead is not considered in the analysis. The reported research

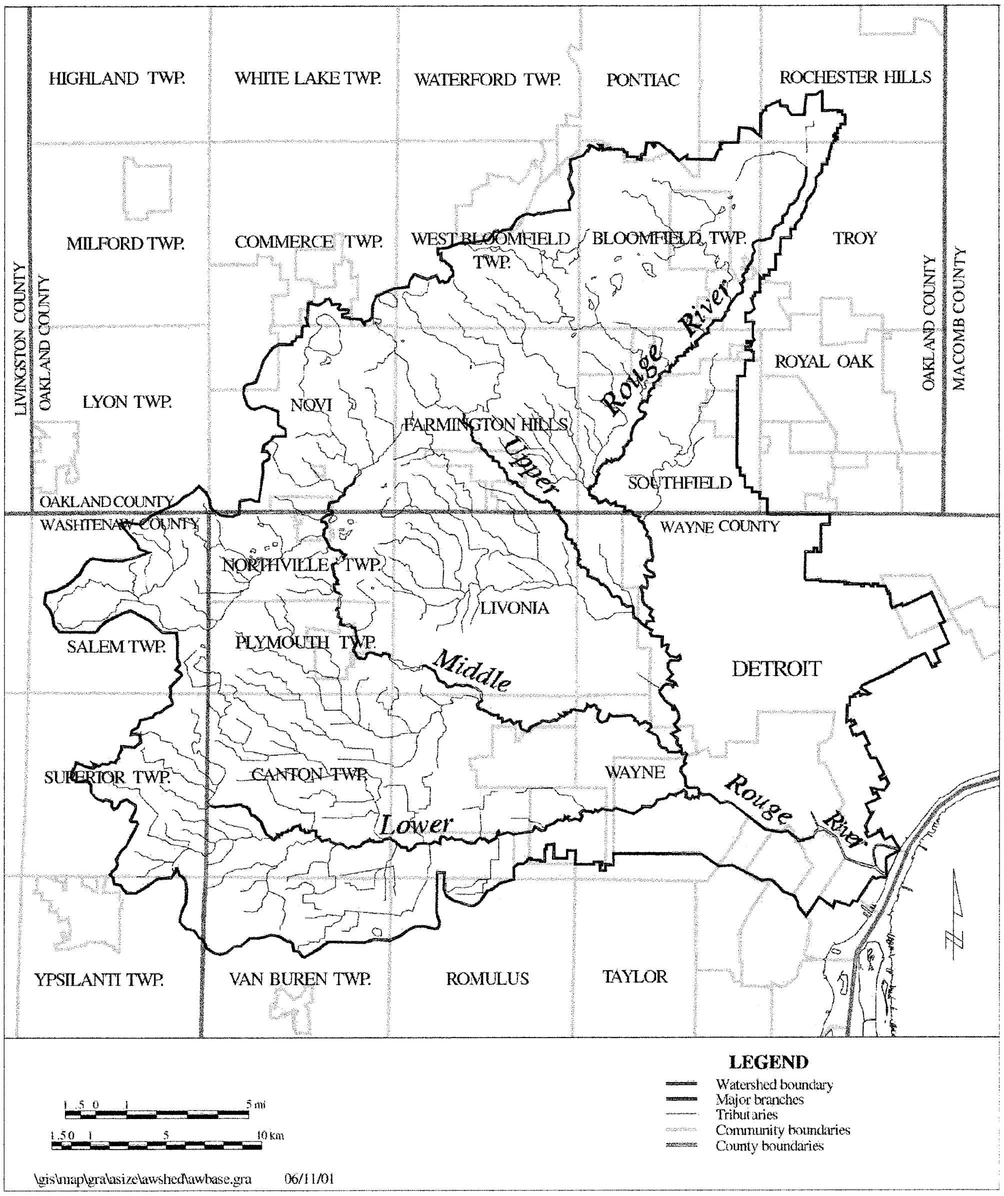

Figure 1. Rouge River Watershed.

uses data from the Rouge River Project's chemical and bacterial sampling programs that monitor instream levels of selected pollutants under both dry and wet conditions. The data used in the reported analysis are drawn from 22 continuous water quality sampling sites so that specific CSO sampling sites were avoided. Two to seven storm events are typically monitored at each site in a given season.

Removal Needed

The median concentrations for the eight pollutants of concern addressed in this paper were calculated based on the Rouge River data from 1998 as well as cumulative data from 1994 to 1999. The 1998 calculations are intended to show the variability across POC over a one-year period. The year 1998 was selected because data for that year were the most recent and complete sampling available. The cumulative data analysis attempts to show the general health of the river and is based on sampling data from long-term monitoring of the Rouge River.

The POC median concentration levels for both the 1998 and cumulative year data were used to estimate the levels of pollutant removal necessary to bring the Rouge River into compliance with current standards. In the case of E. coli, where the geometric mean is the usual measurement method, the researchers chose to use the median figure since some data were missing. There were not five sampling events per month for each reach of the Rouge River from May through October in the years 1994 to 1999, and therefore it was not appropriate to calculate the geometric mean.

Where specific water quality standards have been established for the Rouge River, they were used to calculate the percentage of removal necessary to attain the required water quality (MNREPA, 1994). In other cases, published water quality literature was used to determine the target ambient water quality levels for POC for the river (Harte *et al.,* 1991; Chapman, 1996; CWP, 2000). The percentage of pollutant removal needed was calculated as

$$\text{Removal Needed (\%)} = [(\text{MedConc} - \text{Std})/\text{MedConc}] * 100 \tag{1}$$

where MedConc = the median concentration of the pollutant of concern; and Std = an established government standard, an irreducible concentration, or a recognized level for unpolluted surface water.

Equation (1) assumes that all inputs, including those not being treated, will have the same median concentration and therefore avoids the need to calculate loads. This assumption allows comparisons between concentrations. Total maximum daily load measures were not used as a standard because they have not yet been established for the Rouge River.

To avoid misrepresenting and oversimplifying the water quality of a heterogeneous 126-mile river, the data were stratified based on relative levels of impervious cover. For each sampling station, levels of imperviousness for the surrounding area were calculated from estimates of the percent impervious cover for each subwatershed. These estimates were obtained from the Rouge River Project (Carl Johnson, PE, Camp Dresser McKee, personal communication, July 17, 2001). Each sampling station was categorized based on the average impervious cover from its contributing area. By stratifying the sampling stations in this way, a rough analysis of the effects of increasing urbanization on BMP removal efficiency is possible. Table 1 illustrates the placement of the water quality data and removal percentages needed into three groups based on the percentage of imperviousness associated with the sampling sites (i.e., less than 20 percent, 20 to 40 percent, and more than 40 percent).

Best Management Practices Removal Efficiencies

The storm water management practices examined in this study are: wetland creation and restoration, grassed swales, dry ponds, wet ponds, filtration practices (e.g., surface sand filters), and infiltrations practices (e.g., porous pavement). These BMPs represent an array of conventional storm water control practices commonly undertaken in urban and exurban watersheds (CWP, 1997, 2000; ASCE, 2000; Barrett, 2000; Roesner *et al.,* 2001; Strecker *et al.,* 2001). As such, they represent a reasonable set of storm water treatment practices for the reported examination of the ability of structural BMPs to remove the levels of POC necessary for meeting the applicable water quality standards in an urban watershed.

Pollution removal efficiencies, usually referred to as percentages, describe the ability of a management practice to reduce pollutant levels between the inflow and the outflow of the management system. As mentioned before, the projected pollutant removal efficiencies associated with the structural practices in use on the Rouge River (RRNWWDP, 1996) are generally consistent with removal efficiency estimated for structural practices in the NPRPD (CWP, 2000). Because there is insufficient and inadequate data on structural practice removal efficiencies in the Rouge River, the reported research uses generally accepted structural practice removal efficiencies from the NPRPD data for its the analysis. The NPRPD data are based on completed studies and include 139 studies of storm water treatment practices (STPs) over a 20-year period (CWP, 2000).

BMP pollutant removal efficiencies are not straightforward, and a wide variety of methods have been employed in calculated removal efficiencies (Strecker *et al.,* 2001). Despite the variety in ways to compute removal efficiencies for storm water management practices, the STP Database does not adjust removal efficiencies in its database. It is beyond the scope of this paper to compute and analyze alternative removal efficiency computational forms. Therefore, the reported research relies on the removal efficiencies of structural storm water treatment practices reported in the STP Database (CWP, 2000). However, it must be noted that percent BMP removal efficiencies have been criticized as inappropriate measures of BMP effectiveness not only due to the inconsistent method, but also because they may potentially mischaracterize some practices as less effective (Strecker *et al.,* 2001).

The Center for Watershed Protection (CWP, 2000) notes that STP removal efficiency results should be used to examine the general removal capability of various methods as well as designs. The reported median removal values are based on the broad spectrum of studies that make up the database. Furthermore, the median removal percentages represent the BMP's removal capacity under a variety of climatic and physiological conditions. The data used by the authors to determine general removal capabilities for

TABLE 1. Percentage of Pollutant Removal Necessary in Rouge River.

Pollutants of Concern	Water Quality Standard	Impervious (percent)	1998 Median Levels	Removal Needed From Median 1998 (percent)	1994 to 1999 Median Levels	Removal Needed From Median 1994 to 1999 (percent)
BOD_5		< 20	2.00	0.00	2.60	23.08
(mg/l)	2.0 mg/l[1]	20 to 40	3.50	42.86	3.50	42.86
		> 40	4.70	57.45	3.35	40.30
		Total	**3.80**	**47.37**	**3.35**	**40.30**
		1:4 Quartile	**2.70:19.60**		**3.18:19.20**	
Bacteria (E_coli)		< 20	900.00	85.56	518.00	74.90
(No./100 ml)	130/100 ml[2]	20 to 40	1,900.00	93.16	800.00	83.75
		> 40	3,360.00	96.13	2,500.00	94.80
		Total	**1,735.00**	**92.51**	**1,112.00**	**88.31**
		1:4 Quartile	**787.50:83,200.00**		**508.00:200,000.00**	
Phos_T		< 20	0.04	–	0.09	–
(mg/l)	.15 mg/l[3]	20 to 40	0.07	–	0.10	–
		> 40	0.11	–	0.06	–
		Total	**0.07**	**–**	**0.10**	**–**
		1:4 Quartile	**0.03:0.50**		**0.08:0.36**	
NO_3+NO_2		< 20	1.30	84.62	0.47	57.45
(mg/l)	.2 mg/l[1]	20 to 40	1.40	85.71	0.6	66.67
		> 40	2.40	91.67	0.0	N/A
		Total	**1.40**	**85.71**	**0.60**	**66.67**
		1:4 Quartile	**1.20:5.00**		**0.00:8.50**	
TKN	< 20	2.80	57.14	0.66	–	
(mg/l)	1.2 mg/l[3]	20 to 40	1.70	29.41	0.85	–
		>40	1.70	29.41	0	–
		Total	**1.70**	**29.41**	**0.70**	**–**
		1:4 Quartile	**1.70:2.80**		**0.00:2.00**	
TSS		< 20	14.00	–	34.00	11.76
(mg/l)	30 mg/l[3]	20 to 40	75.00	60.00	52.00	42.31
		> 40	71.00	57.75	71.00	57.75
		Total	**70.50**	**57.45**	**45.50**	**34.07**
		1:4 Quartile	**21.76:1136.00**		**34.30:220.90**	
Cu_T	< 20	5.00	–	5.00	–	
(ug/l)	13 ug/l[4]	20 to 40	5.00	–	5.00	–
		> 40	5.50	–	5.00	–
		Total	**5.00**	**–**	**5.00**	**–**
		1:4 Quartile	**5.00:1300.00**		**5.10:264.40**	
Zn_T		< 20	58.00	18.97	33.00	–
(ug/l)	47 ug/l[4]	20 to 40	68.00	30.88	57.00	17.54
		> 40	89.50	47.49	70.00	32.86
		Total	**70.50**	**33.33**	**57.00**	**17.54**
		1:4 Quartile	**51.00:280.00**		**37.00:131.00**	

[1]Level for Unpolluted Surface Water (Chapman, 1996).
[2]USEPA/MDEQ Surface Water Quality Guideline.
[3]Based upon Irreducible Concentration, (CWP, 2000).
[4]USEPA Aquatic Wildlife Protection Guideline.

BOD_5 = Biochemical Oxygen Demand - five-day incubation
E_Coli = Escherichia coli
Phos_T = Total Phosphorous
$N0_3$+NO_2 = Nitrate and Nitrite Nitrogen
TKN = Total Kjeldahl Nitrogen
TSS = Total Suspended Solids
Cu_T = Total Copper
Zn_T = Total Zinc

each BMP are based on "best condition" values. Finally, the actual performance of a BMP in the field may be influenced by a variety of factors including STP geometry, site characteristics, and monitoring methods. The STP database does not quantify the relative influence of individual site factors.

RESULTS

Table 1 presents the results of the compilation and analysis of the Rouge River data for eight pollutants of concern for 1998 and cumulatively for the years 1994 to 1999. Table 1 shows the percentage removal needed as described in Equation (1) for each pollutant of concern. The table also shows the first and fourth quartiles for POC levels to reflect the variability associated with the levels of each POC in the Rouge River. Additionally, data for each POC are stratified by the percentage of impervious cover for the river.

The data show that five of the eight pollutants of concern in the Rouge River exceed water quality standards for both 1998 and the period from 1994 to 1999. The three POC that require no further removal were total phosphorous and copper levels for both 1998 and 1994 to 1999 and TKN for 1994 to 1999. However, when one considers the variability represented by the fourth quartile of data, total phosphorous, copper, and TKN all exceed their respective water quality standards by significant amounts.

Table 1 also illustrates the tendency of an increase in pollutants of concern in areas with increased percentages of impervious cover. There appear to be two exceptions to this trend, TKN in 1998 and Phos_T from 1994 to 1998. The small decrease of these two POC in the face of increasing urbanization may be explained by the agricultural and open space nature of these pollutants. Both TKN and Phos_T are generally more prevalent in agricultural, more pervious land use areas.

Table 2 summarizes the median pollutant removal percentages of the six storm water treatment practices addressed in this study (CWP, 2000). The removal efficiencies of each storm water treatment practice should not be regarded as a fixed or constant value, but rather as an estimate of long-term performance. Consequently, where the CWP database provided the first standard deviation of removal efficiency for the BMP, it is presented in Table 2 as a way to reflect the variability associated with the BMP removal rates.

Table 2 appears to indicate that wet ponds and wetlands are effective at removing all eight of the pollutants of concern under investigation. Filtering practices also appear promising in their ability to remove an array of pollutants. However, filtering practices seem problematic in their ability to remove nitrate and nitrite. In fact, several studies have concluded that filtering practices actually increase the levels of these two pollutants (CWP, 2000). A similar finding has been reported in CWP (2000) regarding swales and levels of bacteria.

TABLE 2. Storm Water Treatment Practice Median Pollutant Removal Percentages and First Standard Deviation.

Pollutant of Concern	Storm Water Treatment Practice					
	Dry Ponds	**Wet Ponds**	**Wetlands**	**Filtering Practices[1]**	**Infiltration Practices**	**Swales**
Organic Carbon[2]*	25	43	18	54	18[4]	69
Bacteria[3]*	78[5]	70	78[5]	37	5[4]	-25[5]
Phos_T	19 ± 13	51 ± 21	49 ± 36	59 ± 38	70 ± 24	34 ± 33
NO_3+NO_2	4 ± 23	43 ± 39	67 ± 54	-14 ± 47	82[5]*	31 ± 49
TKN		26 ± 25	24 ± 25	61 ± 10		
TSS	47 ± 32	80 ± 27	76 ± 43	86 ± 23	95[5]	81 ± 14
Cu_T	26[5]*	57 ± 22	40 ± 45	49 ± 26	N/A	51 ± 40
Zn_T	26 ± 37	66 ± 22	44 ± 40	88 ± 17	99[5]*	715 ± 36

[1]Excludes vertical sand filters and filter strips.
[2]Organic Carbon Data includes BOD, COD, and TOC removal data.
[3]Bacteria data include fecal streptococci, enterococci, fecal coliform, E. Coli, and total coliform.
[4]Refers to open channel practices not designed for water quality.
[5]Data based on fewer than five data points.
*First standard deviation not available from source.
Source: National Pollution Removal Performance Database, Center for Watershed Protection, 2000 (CWP, 2000).

To test the hypothesis that structural BMPs are not capable of removing the quantity of pollutants of concern required to attain the desired level of water quality, the median pollutant removal percentages for storm water treatment practices (Table 2) were compared to the percentage removal from the median needed (Table 1). Figures 2, 3, and 4 illustrate the comparisons of BMP (also called STP) removal efficiencies and the removal percentages needed for each pollutant of concern for 1998, for 1994 to 1999, and for highly urbanized areas (greater than 40 percent imperviousness).

It should be noted that the STP database measured total bacteria, which includes fecal streptococci, fecal coliform, E. coli, and total coliform. In contrast, the Rouge River data was based on E. coli, whose levels would be necessarily less than those for total bacteria. Similarly, the STP database measured organic carbon content, which includes BOD_5, COD, and TOC removal rates, while the Rouge River data is based only on BOD_5, not organic carbon. As a result, the multiple constituents in both bacteria and organic carbon POC results in the need to acknowledge the imperfect data and limitations. The STP removal capacities reported address aggregate efficiencies for organic carbon and total bacteria, while the Rouge River data address BOD_5 or E. coli alone. These POC levels and removal efficiencies are not directly comparable measures and must be kept in mind.

Figure 2 illustrates that for five pollutants of concern at levels exceeding clean water standards in 1998, the STPs vary in their ability to attain the respective water quality objectives. Figures 2, 3, and 4 use a thick black line to demonstrate the level of pollutant removal needed (as a percentage) with symbols for each STP above, below, or on the pollutant removal needed line for each pollutant of concern. If an STP is above the thick black line, then that particular STP is capable of removing enough of the pollutant to achieve the desired water quality. While all six STPs have the ability to address the 1998 levels of phosphorous and copper, only filtering practices seem

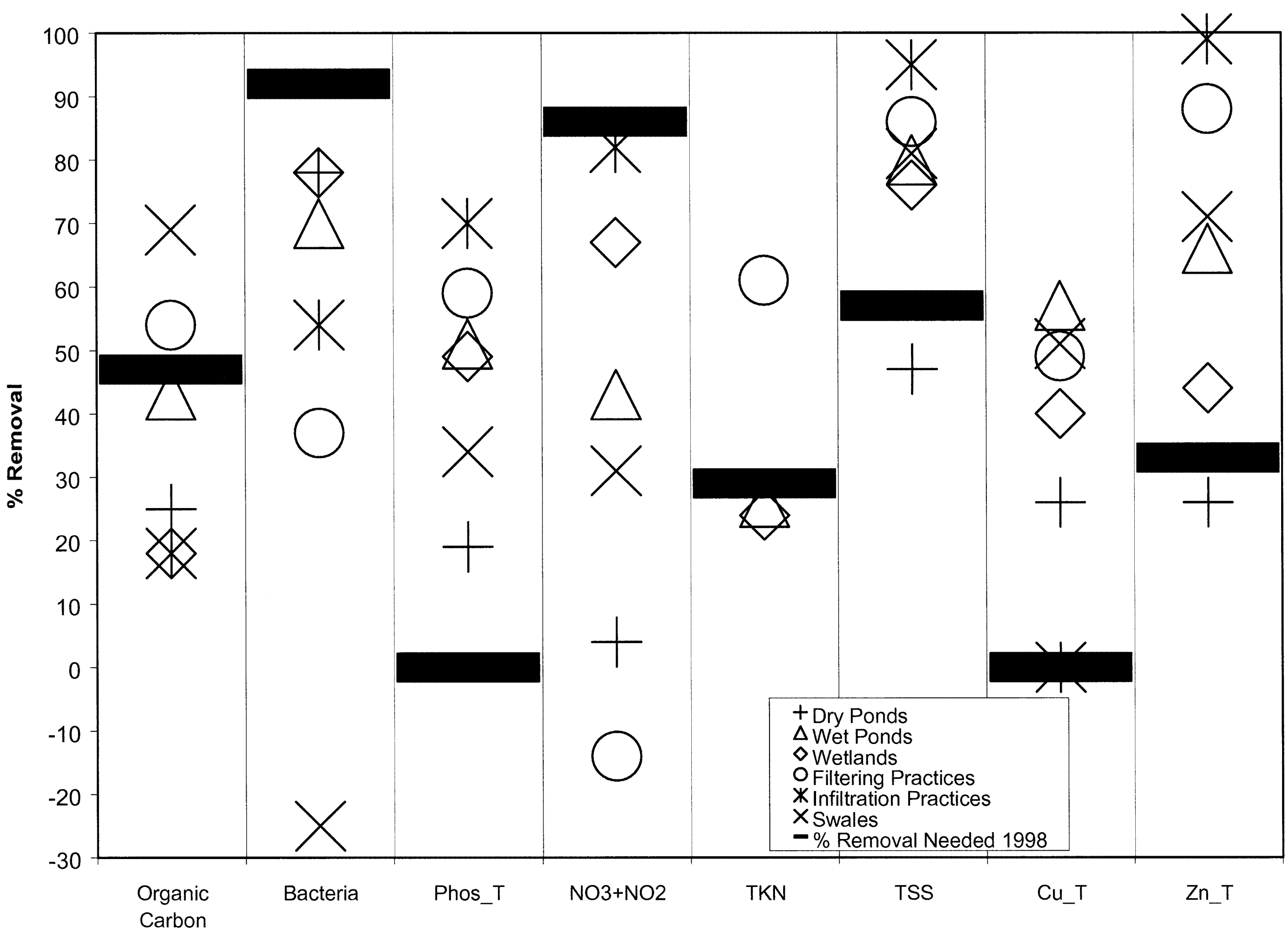

Figure 2. Removal Efficiencies and Removal Needed for Rouge River (1998 data).

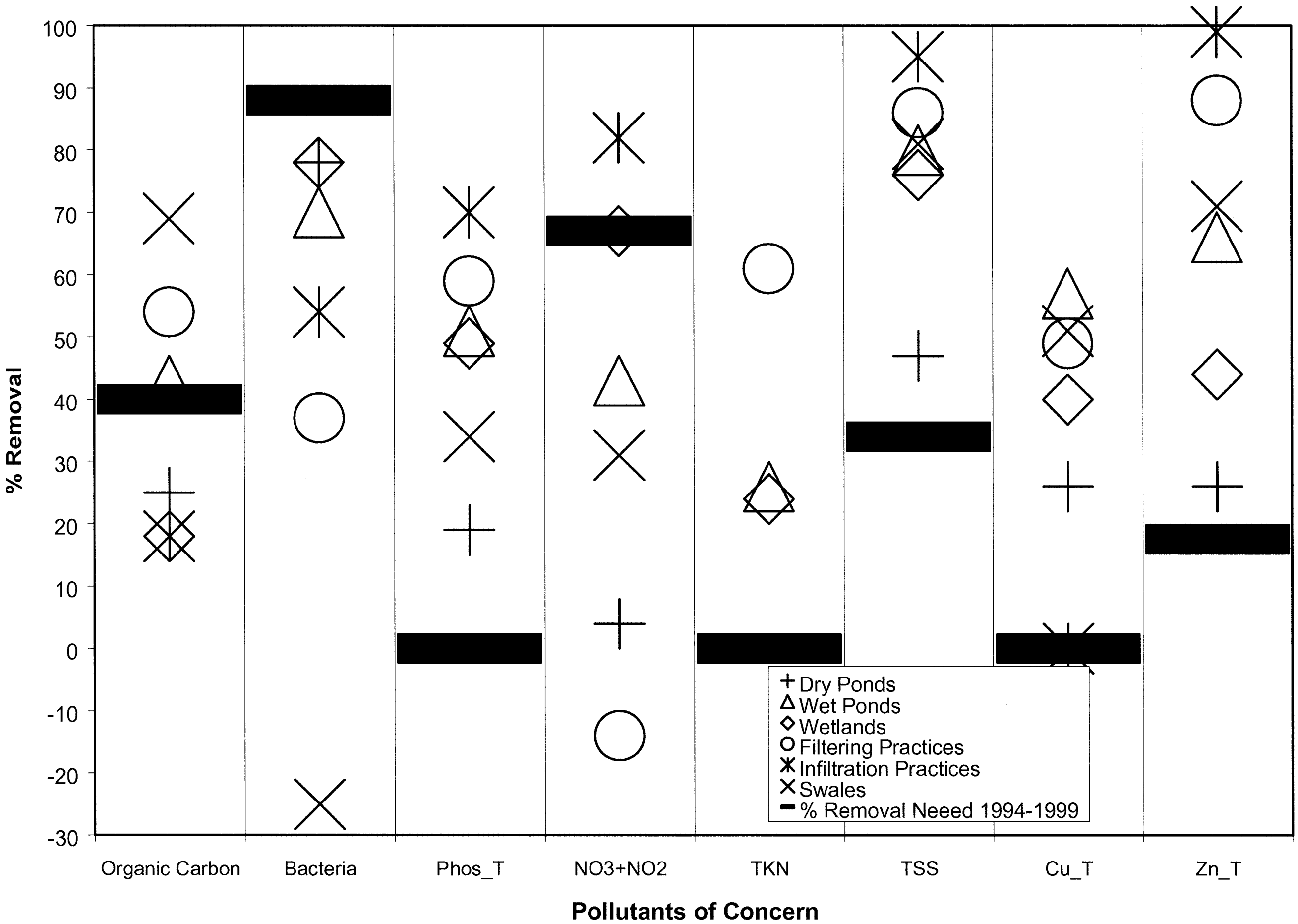

Figure 3. Removal Efficiencies and Removal Needed for Rouge River (1994 to 1999 data).

capable of adequately addressing TKN. Equally apparent are the remaining problems of bacteria, NO_3, and NO_2, where none of the STPs appear capable of removing the necessary levels associated with these pollutants.

Figure 3 illustrates the data for the period from 1994 to 1999 and shows that five of the eight pollutants require some removal in order to attain water quality objectives for the Rouge River. The comparison of the level of removal needed to the STP's removal efficiencies again produces mixed results. All six STPs are capable of removing the TSS, total phosphorous, and zinc levels based on the 1994 to 1999 data. However, none of the STP appear able to adequately reduce the bacteria levels. During this time period, it seems that the STP's removal abilities vary for the nitrite, nitrate, and organic carbon levels. Based on the data from 1994 to 1999, it appears that both filtering and infiltration practices are able to address three of the five POC that exceed water quality standards.

Extending this analysis to the densest urban areas of the watershed, Figure 4 demonstrates that in areas with more than 40 percent of land cover by impervious surfaces, the levels associated with bacteria are again beyond the treatment capabilities of all the STPs. Figure 4 also illustrates how the amount needed for removal of pollutants of concern has increased for TSS and zinc and that fewer STPs seem capable of treating the increased pollution levels for these POC. In fact, no one pollutant of concern seems to be adequately treatable by all of the STPs. It does appear that infiltration and filtering practices remain consistently better at addressing excess levels of nutrients, TSS, and total zinc.

Comparison of this study to previously RRNWWDP modeled pollution levels and remediation scenarios, based on water quality monitoring from September 1993 to July 1994, was undertaken in order to validate this studies methodology as well as obtain a clearer picture of watershed health based on longer term monitoring. Seven POC were common to both the modeling results and this study. However, the

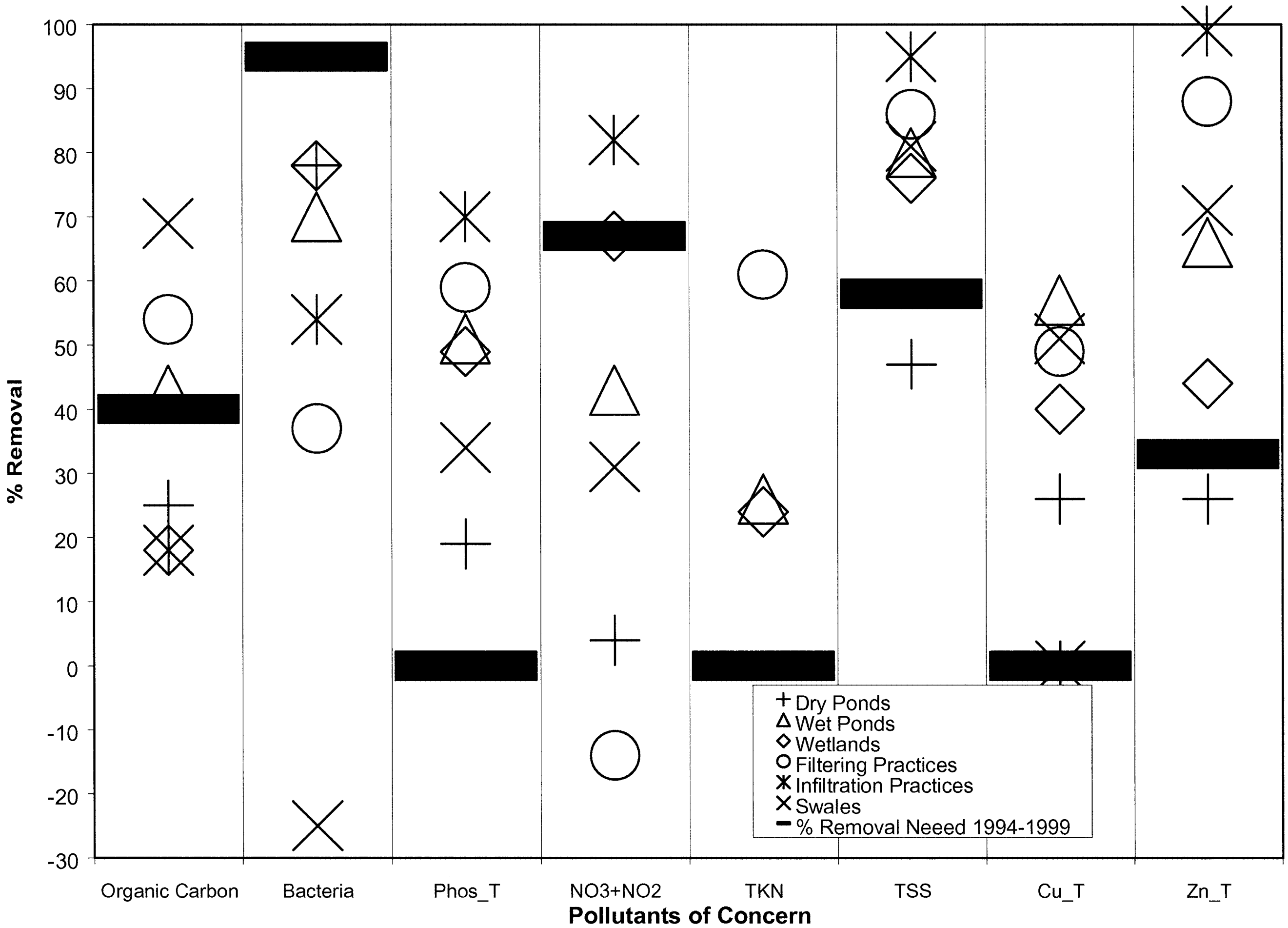

Figure 4. Removal Efficiencies and Removal Needed for Urbanized Areas of the Rouge River (1994 to 1999).

modeling results used fecal coliform, whereas this study used E. coli, therefore not permitting direct comparison of bacterial counts.

The monitoring results from 1998 and 1994 to 1999 were modeled using the RRNWWDP Watershed Management Model (WMM). The RRNWWDP's WMM is used to support the development of watershed management plans. The WMM establishes an overall "framework" for simulating the generation and fate of pollutant loads from a number of sources and assesses control strategies. The RRNWWDP approach is subdivided into three tiers – small area (Tier 1), subareas (Tier 2), and watershed wide (Tier 3). This multiple scale approach allows for examination in detail of a variety of pollution generation, removal, and treatment processes on one scale and allows transfer of those findings to a watershed wide analysis (RRNWWDP, 1994a). Tier 1 analysis examines the physical processes of pollutant accumulation, transport, and treatment. Because the load factors are based largely on single land use monitoring data, the estimators can be applied to small, homogenous areas to analyze pollutant buildup and assess the pollutant reduction of various treatment activities. Tier 2 modeling performs load allocations and develops flows and loads for input into the WMM water quality model (Tier3). The loads developed for each subarea (Tier 2) can then be used as inputs into the watershed wide Rouge River WMM Model. Data required to use the WMM include storm water event mean concentrations (EMCs) for each pollutant type, land use with the areas served by septic systems identified, average annual precipitation, annual baseflow and average baseflow concentrations, point source flows and pollutant concentrations, and average CSO flows and concentrations. The storm water pollutant factors (event mean concentrations) developed for the models are sufficient for use in all simulations of water quality in the Rouge River (RRNWWDP, 1994b). The WMM model's validity has been established through its application in numerous watershed projects throughout the United States (CDM, 1992; Simons, Li and Associates, Inc., 1995).

Table 3 compares the percentage of removal needed to meet water quality standards reported in this study with the range of percentage removals anticipated from various combined sewer overflow (CSO) and storm water management controls (wet detention ponds) modeled using the WMM at the 1993 and 1994 POC levels. The CSO and storm water controls were based on Michigan Department of Environmental Quality recommendations. If the modeled percentage removal efficiencies either contain or exceed the percentages needed to attain water quality standards, then the proposed STP should be effective. Table 3 shows that the nitrate and nitrite levels exceed those originally modeled using the prescribed interventions. Furthermore, the 1998 BOD and TKN levels were greater than those originally modeled. This means that three of the seven pollutants of concern pose a problem for the pollution control scenarios modeled for the watershed. Furthermore, these findings are consistent with the findings of this study.

To test the hypothesis that STP removal efficiency decreases with increases in levels of imperviousness, Mann-Whitney U tests were performed between the three levels of imperviousness for each POC (less than 20 percent, 20 to 40 percent, and more than 40 percent) using the 1994 to 1999 figures. The results indicate a significant difference (≤ 0.05 level) between the concentration levels of POC for 16 of the 20 tests (see Table 4). Both total phosphorous and total copper did not vary by level of imperviousness. This might have been expected, since neither POC was present at levels requiring removal in order to meet water quality standards. Also, there was no significant difference between the 20 to 40 percent level and the more than 40 percent level for BOD_5 and total zinc. This may simply be because once a certain level of urbanization has been reached, these particular POC may not continue to vary with the level of imperviousness. On the whole, with two-thirds of the tests indicating a difference in the level of POC concentrations, it can be concluded that removal efficacy of the STPs already existing in the Rouge River declines as impervious area increase.

Table 5 demonstrates how the results of the analysis address the hypothesis that removal efficacy of STPs declines as impervious area increases. Table 5 is divided into three sections based on the three levels of impervious cover used in the study. For each level of imperviousness, a comparison of the STP's (i.e., BMP's) apparent capability to remove each POC is made. If the data show that an STP is able to lower the level of a POC to meet the water quality standard, then it is indicated by a check mark. A total number of check marks for each POC and a grand total for each level of imperviousness are also calculated. At the less than 20 percent level of imperviousness, there are 36 cases where STP are able to remove the necessary levels of pollutants to meet water quality standards. At the 20 to 40 percent level of imperviousness, there were 31 cases in which the STPs are able to remove enough POC to meet requirement water quality standards, and at the more than 40 percent level, there were 27 such cases. Therefore, it appears that the ability of STPs to treat each POC does diminish as the level of imperviousness increases.

TABLE 3. Comparison of Percent Removal Needed to Meet Water Quality Standard With the Modeled Percent Change From Existing Average Annual Pollution Loadings Under Selected Pollution Control Scenarios.

	Study Results		**Rouge River Model[1,2,3,4]**
Pollutant of Concern	**Removal Needed From 1998 Median to Attain Water Quality Standard (percent)**	**Removal Needed From 1994 to 1999 Median to Water Quality Standard (percent)**	**Change Needed From Existing Total Mean Annual Pollution Loadings (percent)**
BOD_5	**47.37**	40.30	37 to 42
Bacteria	92.51	88.31	NA
Phos_T	–	–	34 to 43
NO_3+NO_2	**85.71**	**62.62**	3 to 11
TKN	**29.41**	–	23 to 27
TSS	57.45	34.07	42 to 61
Cu_T	–	–	13 to 46
Zn_T	33.33	17.54	1 to 31

[1]Model does not include point sources downstream of Greenfield Road.
[2]Model range is based on three storm water treatment practice levels in combination with combined sewer overflow management options.
[3]Model is based on Michigan Department of Environmental Quality 1997 guidelines.
[4]As reported in Preliminary Pollution Loading Projections for the Rouge River Watershed (1996).

TABLE 4. Mann-Whitney Test Results Determining if the Concentration of Each POC Differs Between the Levels of Imperviousness.

Pollutant of Concern	Level of Imperviousness (percent)		Mann-Whitney N	Mann-Whitney U		Mann-Whitney Z	Significance Level
BOD_5	< 20	(a)	123	(a-b)	16,665.50	-2.61	.009*
	20 to 40	(b)	322	(a-c)	7,731.00	-3.49	.000*
	> 40	(c)	165	(b-c)	24,408.50	-1.47	**.141**
Bacteria	< 20	(a)	35	(a-b)	6,085.50	-2.27	.023**
	20 to 40	(b)	452	(a-c)	1,611.00	-5.14	.000*
	> 40	(c)	202	(b-c)	30,164.00	-6.94	.000*
Phos_T	< 20	(a)	55	(a-b)	6,177.50	-1.49	**.136**
	20 to 40	(b)	257	(a-c)	3,158.00	-0.29	**.774**
	> 40	(c)	118	(b-c)	14,250.00	-0.94	**.347**
NO_3+NO_2	< 20	(a)	61	(a-b)	1,046.00	-5.19	.000*
	20 to 40	(b)	72	(a-c)	13.00	-3.73	.000*
	> 40	(c)	6	(b-c)	38.00	-3.34	.001*
TKN	< 20	(a)	19	(a-b)	380.00	-1.94	.050**
	20 to 40	(b)	57	(a-c)	6.00	-3.25	.001*
	> 40	(c)	6	(b-c)	70.00	-2.37	.016**
TSS	< 20	(a)	128	(a-b)	13,791.50	-5.91	.000*
	20 to 40	(b)	334	(a-c)	5,330.50	-8.08	.000*
	> 40	(c)	181	(b-c)	23,541.00	-4.15	.000*
Cu_T	< 20	(a)	29	(a-b)	889.00	-0.24	**.812**
	20 to 40	(b)	63	(a-c)	251.50	-0.24	**.809**
	> 40	(c)	18	(b-c)	559.00	-0.11	**.916**
Zn_T	< 20	(a)	43	(a-b)	1,235.50	-2.48	.013**
	20 to 40	(b)	79	(a-c)	346.50	-2.22	.027**
	> 40	(c)	24	(b-c)	842.00	-0.83	**.408**

*Impervious levels are different from one another at the 0.01 level of significance.
**Impervious levels are different from one another at the 0.05 level of significance.

DISCUSSION

The data show that it seems unlikely that urban water quality goals can be met by using only the most common storm water treatment practices. A good number of the common pollutants of concern in the Rouge River and other urban watersheds present particularly difficult challenges for typical STPs. As shown in Table 1, bacteria requires upwards of 88 percent removal from the Rouge River to meet full body contact standards. This is particularly interesting because by law this POC should not even be reaching receiving waters. The data suggest that the conventional STP removal efficiencies fall short of being able to attain the required bacterial levels in the Rouge River's urban watershed.

The data also show that many STPs do not remove dissolved constituents, such as nitrate and nitrite, to a sufficient degree. While filtering practices appear capable of removing several POC, these STPs have low levels of nitrogen removal capacity and are associated with increasing nitrate and nitrite levels in receiving waters. As noted elsewhere, STPs can reduce the level of eutrophication, as indicated by the difference in removal efficiencies between TKN, NO_3, and NO_2, but strict compliance with water quality standards is doubtful (Barrett, 2000).

The data also demonstrate that most STPs are capable of removing total phosphorous, copper, and zinc to satisfactory levels. However, when loads associated with extreme weather events, particularly in urbanized areas, are compared to STP removal efficiencies, it may be that STPs are inadequate for protecting urban waterways. The conventional structural BMPs generally implemented by communities to address the most widespread urban water quality impairment appear insufficient by themselves to adequately improve urban water quality.

TABLE 5. Effectiveness of BMPs by Percent Imperviousness (1994 to 1999 data).

Impervious (percent)	POC	Storm Water Treatment Practices: Dry Ponds	Wet Ponds	Wetlands	Filtering Practices	Infiltration Practices	Swales	Totals
< 20	BOD_5	✓	✓	✓	✓	✓	✓	6
	Bacteria	✓		✓			+	2
	Phos_T	✓	✓	✓	✓	✓	✓	6
	NO_3 and NO_2			✓	+	✓		2
	TKN			✓	✓	✓		3
	TSS	✓	✓	✓	✓	✓	✓	6
	Cu_T	✓	✓	✓	✓	N/A	✓	5
	Zn_T	✓	✓	✓	✓	✓	✓	6
Total number of STP capable of removing the POC present at less than 20 percent impervious								**36**
20 to 40	BOD_5		✓		✓		✓	3
	Bacteria						+	0
	Phos_T	✓	✓	✓	✓	✓	✓	6
	NO_3 and NO_2			✓	+	✓		2
	TKN			✓	✓	✓		3
	TSS	✓	✓	✓	✓	✓	✓	6
	Cu_T	✓	✓	✓	✓	N/A	✓	5
	Zn_T	✓	✓	✓	✓	✓	✓	6
Total number of STP capable of removing the POC present at 20 to 40 percent impervious								**31**
> 40	BOD_5		✓		✓		✓	3
	Bacteria						+	0
	Phos_T	✓	✓	✓	✓	✓	✓	6
	NO_3 and NO_2				+			0
	TKN			✓	✓	✓		3
	TSS		✓	✓	✓	✓	✓	5
	Cu_T	✓	✓	✓	✓	N/A	✓	5
	Zn_T		✓	✓	✓	✓	✓	5
Total number of STP capable of removing the POC present at greater than 40 percent impervious								**27**

✓ = STP is capable of removing the level of POC present in order to attain water quality standards.
\+ = STP increase the level of POC.
N/A = Data not available.

This study's findings support the notion that structural BMPs alone do not adequately reduce the concentrations and/or mass of pollutants of concern to the levels necessary to meet current surface water quality standards. While some particular structural treatment practices do appear adequate for reducing an individual pollutant of concern, as a whole STPs do not appear sufficient for adequately addressing the array of urban pollutants in the Rouge River. Since many BMPs rely upon gravity to settle out pollutants (with NOx being one exception), it is unlikely that removal efficiencies would significantly improve if a chain of BMPs were employed (Barrett, 2000). Furthermore, the data and analysis lend support to the idea that increases in the percentage of impervious area adversely affect the ability of structural BMPs to remove the required concentrations and mass of pollutants of concern. The data clearly show that STPs are less likely to improve water quality in highly urbanized areas.

LIMITATIONS OF STUDY

A major limitation to this study is that it does not reflect the variability associated with the design and location of particular BMPs and their removal efficiencies. It is obvious that all BMPs in a particular category are not created equal. However, BMPs variability would not alter the conclusion that for several POC in the Rouge requiring almost 100 percent removal, none of the BMPs analyzed could achieve such ends.

The results of the reported research might have been different had the sampling dates better coincided with extreme weather events. There was very little correlation between the data sampling dates and the extreme storm events as reported by the National Oceanic and Atmospheric Agency. The absence of water quality data associated with extreme weather means that the pollutants of concern median levels may actually have been even higher than reported as a result of the runoff associated with these storms.

It must also be pointed out that the use of the percentage removal calculation for each BMP is a limitation. As noted by Strecker *et al.* (2001), this method of analyzing BMP efficiency may potentially mischaracterize some practices as less effective because of discrepancies in the water quality entering them as well as the multiple methods used to calculate efficiency. Inconsistent study methods, reporting protocols, and lack of design information (Strecker et al., 2001) make more rigorous comparison of BMP removal efficiencies difficult at this time.

CONCLUSION

The results of the study illustrate that communities are ill advised to rely exclusively on structural BMPs to address their water quality concerns. The data appear to support the value of communities adopting multifaceted watershed approaches for addressing storm water runoff and nonpoint source pollution. The reported results suggest that structural BMPs are not able to achieve water quality objectives by themselves, especially in urbanized areas. Therefore, additional program elements, including those suggested under Phase II regulations such as public education, outreach, and involvement, warrant inclusion in communities' watershed protection activities. Additional nonstructural best management practices that might be considered include: water sensitive urban design, planning controls, legislative controls, and municipal maintenance controls.

Data are scarce for evaluating the effectiveness of nonstructural practices at reducing the impact associated with storm water. In fact, at the present time neither the ASCE (2002) nor the CWP (2000) database reports any findings on nonstructural BMP studies. Future research into the effectiveness of nonstructural BMP should measure both the degree of change in people's habits following implementation of the management program and the degree of reduction of various pollutant sources. At this time, no good quantitative basis is available for defining the appropriate mix of structural and nonstructural initiatives for communities to achieve appropriate storm water management strategies. However, it is clear that structural BMPs have limits and that municipalities would be well served to include nonstructural BMP programs into their watershed management plans to safeguard their waterways for the long term.

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LITERATURE CITED

ASCE (American Society of Civil Engineers), 2000. National Stormwater Best Management Practices (BMP) Database (CD-ROM). American Society of Civil Engineers.

Barrett, M. E., 2000. Structural BMPs: The Solution to Water Quality Problems? *In:* Water Quantity and Quality Issues in Coastal Urban Areas, Robert W. Higgins (Editor). American Water Resources Association, Middleburg, Virginia, TPS-00-3, pp. 373-376.

Berry, K. A., N. L. Markee, M. J. Stewart, and G. R. Giewart, 1996. County Commissioners' Water Knowledge. Water Resources Bulletin 32(5):1089-1099.

Brown, E., A. Perterson, R. Kline-Roback, and L. Wolfson, 2000. Developing a Watershed Management Plan for Water Quality: An Introductory Guide. Institute for Water Research, Michigan State University Extension and Michigan Department of Environmental Quality.

CDM (Camp, Dresser, and McKee), 1992. Watershed Management Model User's Manual (Version 2.0). Prepared for the Florida Department of Environmental Regulation, Tallahassee, Florida.

CWP (Center for Watershed Protection), 1997. Technical Note No. 95: Comparative Pollutant Removal Capability of Stormwater Treatment Practices. Water Protection Techniques 2(4):515-520

CWP (Center for Watershed Protection), 2000. National Pollutant Removal Performance Database for Stormwater Treatment Practices (Second Edition). Center for Watershed Protection, Ellicott City, Maryland.

Chapman, D., 1996. Water Quality Assessments (Second Edition). E and FN SPON, London, United Kingdom.

Harte, J., C. Holdre, R. Schneider, and C. Shirley, 1991. Toxics A to Z. University of California Press, Berkeley, California.

Jones, Jonathan E., 2001. BMP Performance and Receiving Water Impacts. Water Resources IMPACT 3(6):2.

MNREPA (Michigan Natural Resources and Environmental Protection Act), 1994. PA 451, Part 31, R323.1041-1117. As amended in 1999 by the State of Michigan.

Murray, J., K. A. Cave, and D. S., Bryson, 1999. Wet Weather Control Demonstration Activities in Southeast Michigan: Some Lessons Learned. Water Science and Technology 39(12):273-282.

Roesner, L. A., B. P. Bledsoe, and R. W. Brashear, 2001. Are Best Management Practices Criteria Really Environmentally Friendly? Journal of Water Resources Planning and Management, May/June, pp. 150-154.

RRNWWDP (Rouge River National Wet Weather Demonstration Project), 1994a. Technical Memorandum: Approach to Simulating the Water Quantity and Quality in the Rouge River. (MOD-TM26.00). Wayne County, Department of Environment, Wayne County, Michigan.

RRNWWDP (Rouge River National Wet Weather Demonstration Project), 1994b. Selection of Storm Water Pollutant Loading Factors. (MOD-TM34.00). Wayne County, Department of Environment, Wayne County, Michigan.

RRNWWDP (Rouge River National Wet Weather Demonstration Project), 1996. Interim Final Report: Pilot Best Management Practice Projects (319 Grant) (RPO-NPS01A-TR02.01). Department of Environment, Wayne County, Michigan.

RRNWWDP (Rouge River National Wet Weather Demonstration Project), 1998. Field Sampling Plan: 1998 Baseline Water Quality Sampling (RPO-WMGT-FSP19.00). Department of Environment, Wayne County, Michigan.

RRNWWDP (Rouge River National Wet Weather Demonstration Project), 2000. RPO DataView CD Volume. 6 [CD-ROM].

RRNWWDP (Rouge River National Wet Weather Demonstration Project), 2001a. An Overview of the Rouge River. Wayne County. *Available at* http://www.wcdoe.org/ rougeriver/2001. *Accessed on* October 19, 2001.

RRNWWDP (Rouge River National Wet Weather Demonstration Project), 2001b. Watershed Progress: Rouge River Watershed, Michigan. Wayne County. *Available at* http://www.wcdoe.org/rougeriver/geninfo/progress/progress.html. *Accessed on* November 20, 2001.

Simons, Li and Associates, Inc, 1995. Tucson Storm Water Management Study Phase II, Storm Water Master Plan. Camp Dresser and McKee, Lewis and Roca, Rillito Consulting Group, SWCA, Inc. *Available at* http://www.azstarnet.com/public/water/strmhome. htm. *Accessed on* June 16, 2003.

Strecker, E. W., M. M. Quigley, B. R. Urbonas, J. E. Jones, and J. K. Clary, 2001. Determining Urban Storm Water BMP Effectiveness. Journal of Water Resources Planning and Management, May/June, pp. 144-149.

Urbonas, Ben, R., 2001. Protecting Our Receiving Waters With BMP. Water Resources IMPACT 3(6):3-6.

USEPA (U.S. Environmental Protection Agency), 1999. NPDES Revisions Addressing Storm Water Discharges, 64 F.R. 68722 (1999) (codified at 40 C.F.R. §§ 9,122,123, and 124). *Available at* http://www.epa.gov/owm/sw/phase2. *Accessed on* May 16, 2001.